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ORIGINS OF GPS SURVEYING

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AIR FORCE SYSTEMS COMMAND
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FIELD	GROUP	SUB-GROUP
08	05	--

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Conceptually, GPS geodetic surveying is a descendant of hyperbolic radio-positioning systems such as LORAN and Omega, of the "very long baseline" interferometry technique of radio astronomy, and of satellite Doppler tracking. Satellite Doppler positioning systems such as TRANSIT may have paved the way for GPS politically and economically, but conceptually they were strongly opposed to and probably retarded the development of GPS geodetic surveying.

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83 APR edition may be used until exhausted. All other editions are obsolete.

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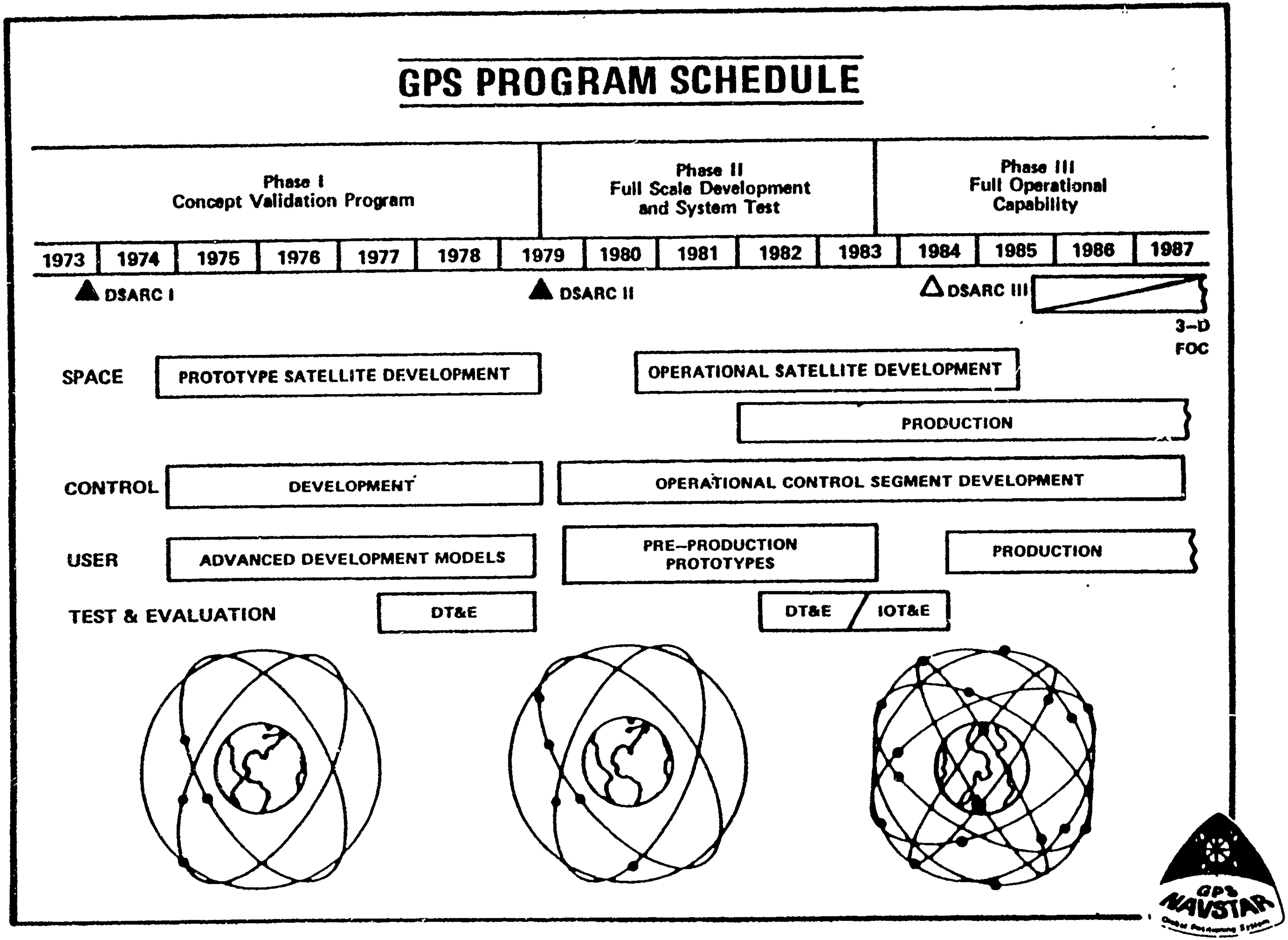
GPS PROGRAM SCHEDULE
Phase I
Concept Validation Program
Phase II
Full Scale Development
and System Test
Phase III
Full Operational
Capability
1973
1974
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DSARC III
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SPACE
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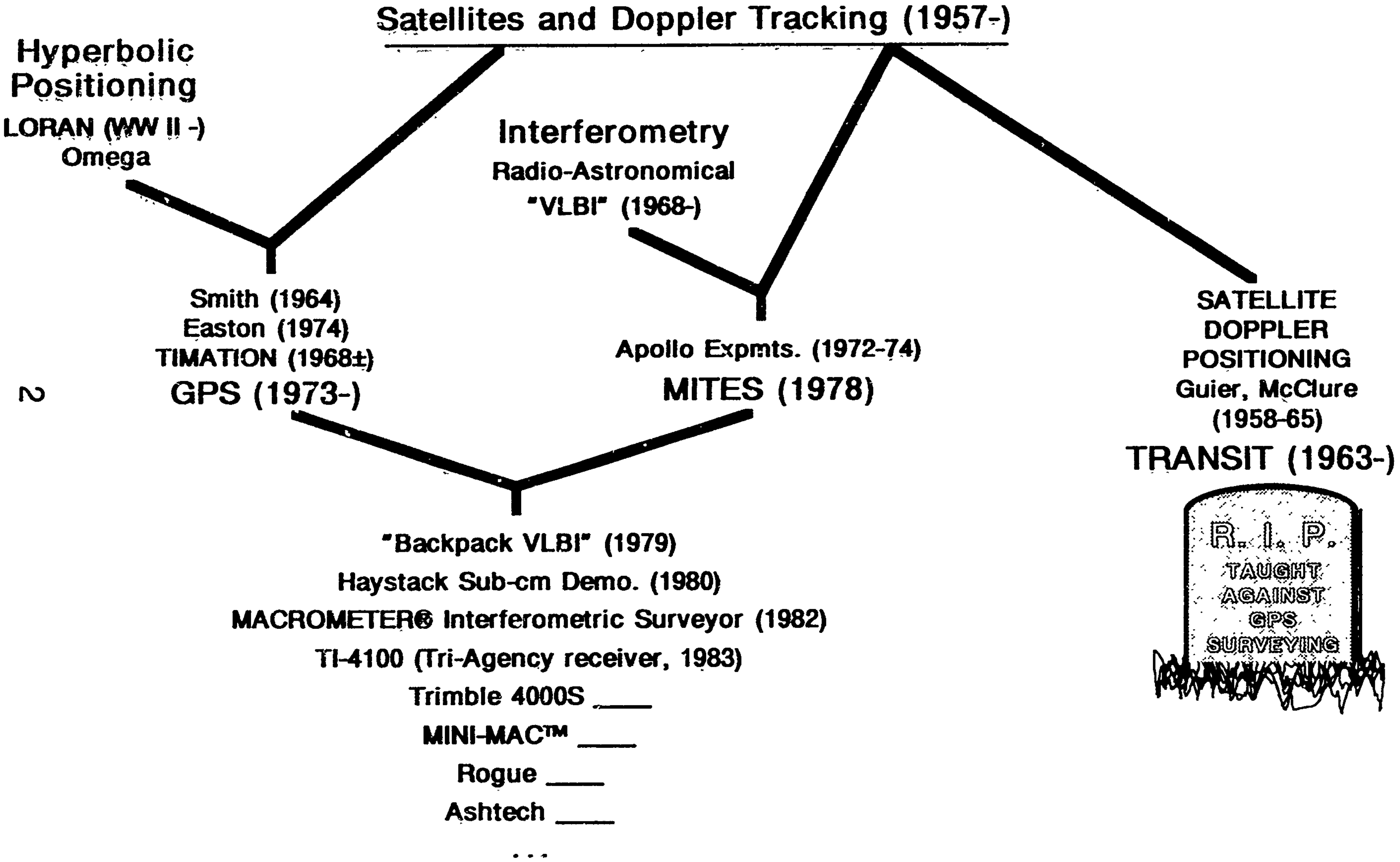
NAVSTAR

Genealogy of GPS Surveying



Radio Observations of the Russian Earth Satellite*

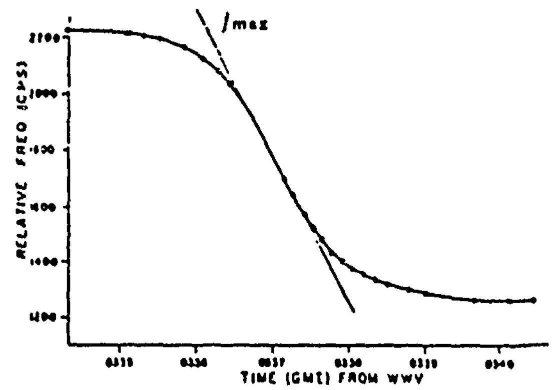


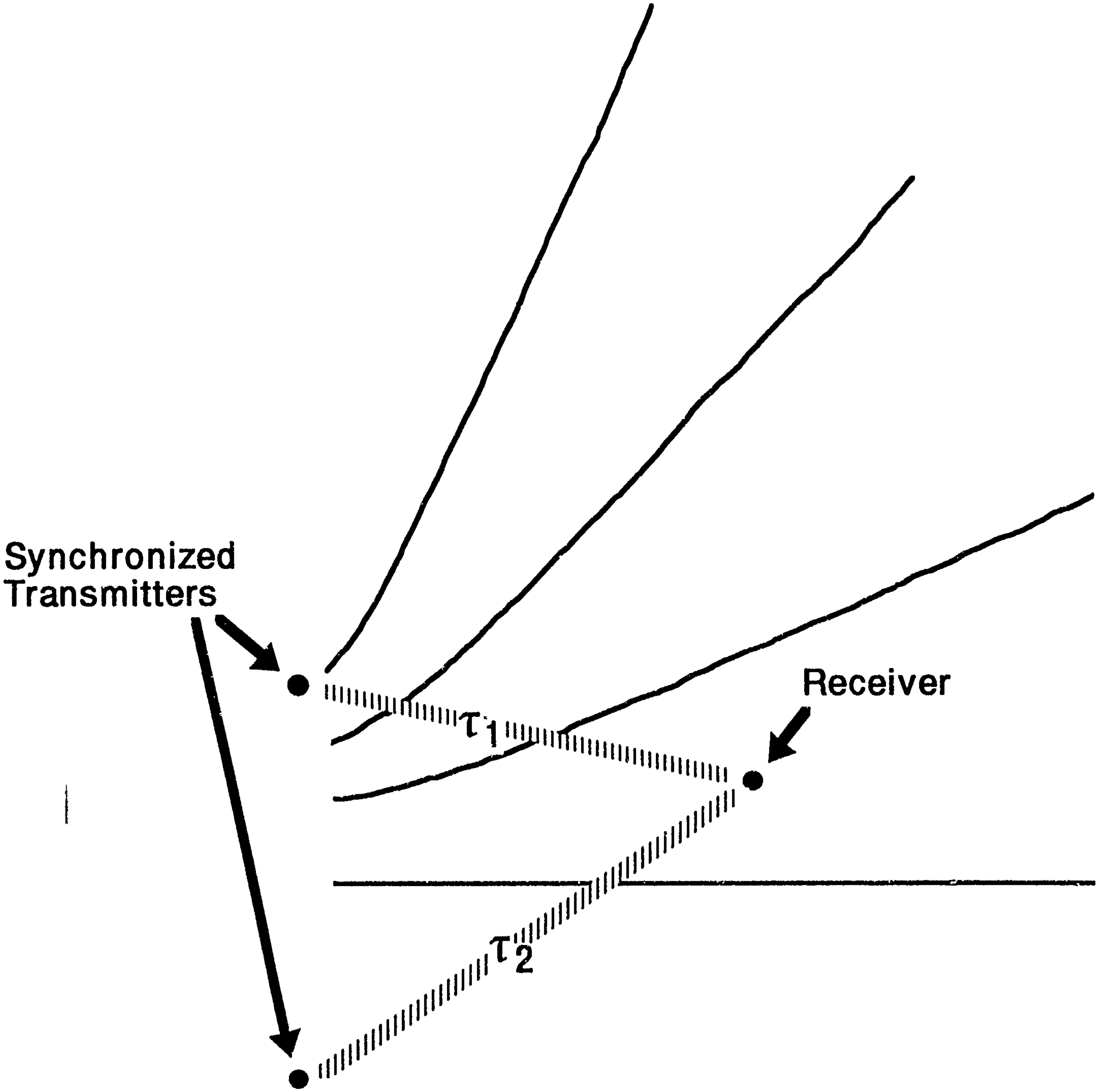
Fig. 1—Round Hill 0335 GMT, October 7, 1957—20 mc.

Simple radio observations of signals from the Soviet satellite of October 4 were made by Lincoln Laboratory beginning on the evening of October 5, 1957. Plots of received frequency vs time, one of which is shown in Fig. 1, were made by analyzing the tape-recorded audio outputs of standard radio receivers which used beat frequency oscillators. By studying the shape of such curves it is possible to determine the slant range of the point of nearest passage of the satellite to the observing point. This distance will be referred to as the miss distance, r_0. This quantity is given by

* Received by the IRE, October 14, 1957. The research in this document was supported jointly by the Army, Navy, and Air Force under contract with the Mass. Inst. Tech.

A few remarks will outline the nature of the calculation. In preparing the prediction of the fourth transit, it was assumed that corresponding tracks on successive nights differed in longitude by a constant amount and had the same altitude above the earth. A value of speed v was first computed using an approximate knowledge of the period and an arbitrarily assumed value of altitude h. This value of v enabled the values of r_0 for the three nights to be computed using the above formula. The three measurements of r_0 were then used to solve for a better value of h which was reinserted in the calculation for v. One such iteration proved to be sufficient to fix v and h and provide the r_0 prediction for the fourth track.

HYPERBOLIC POSITIONING



1

3,126,545

SATELLITE HYPERBOLIC NAVIGATION SYSTEM

Ira D. Smith, Jr., Rome, N.Y., assignor to the United States of America as represented by the Secretary of the Air Force

Filed Nov. 23, 1960, Ser. No. 71,371
6 Claims. (Cl. 343—103)
(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the United States Government for governmental purposes without payment to me of any royalty thereon.

This invention relates generally to navigational systems, and more particularly to a long range hyperbolic navigation system, including a satellite relay station whereupon omnidirectional transmission of position and time information may be accomplished without regard to weather conditions or sky-wave characteristics.

Conventional hyperbolic navigation systems are subject to certain limitations which, in many instances, reduce their practicability. The transmission of pulse information at very high frequencies reduces the effective range of such a system to line-of-sight distances. The use of sky-wave transmission to overcome this limitation is effective only at night and is inherently inaccurate. Systems employing lower frequency transmission are subject to interference from changing weather conditions. This is especially true of electrical disturbances which may render the transmitted pulse information completely unintelligible. A further undesirable feature of current hyperbolic navigation systems is the requirement of a minimum of three fixed transmitting stations. Such stations, being at certain fixed locations, present to the area covered a limited number of predetermined base lines. The inflexibility of such a system precludes the selection of optimum base lines by the majority of ships using said system.

It is accordingly an object of this invention to provide a hyperbolic navigation system that is substantially independent of weather conditions.

It is another object of this invention to provide a novel method of navigating ships at sea wherein said ships are oriented by the several positions of an orbiting satellite station.

It is a further object of this invention to provide a hyperbolic navigation system having greater range and accuracy than has heretofore been possible.

It is a still further object of this invention to provide a hyperbolic navigation system whereby ships using such system may choose any number of optimum base lines.

It is a still further object of this invention to provide a satellite hyperbolic navigation system employing the use of sequential base lines, thereby rendering synchronizing and timing less critical.

It is a still further object of this invention to provide a satellite navigation system of the type described wherein highly accurate orbital computations are unnecessary.

These and other objects, together with the principles of the invention itself, will be described in detail with reference to the accompanying drawings in which:

FIG. 1 presents families of curves illustrating the principles of hyperbolic navigation;

FIG. 2 illustrates the apparatus required to transmit satellite position-time information in accordance with the principles of my invention; and

FIG. 3 illustrates a presently preferred method of navigating a ship by the application of said apparatus and principles.

Referring now to FIG. 1, there is illustrated three stations T_1, T_2 and T_3 which are typical of a conventional

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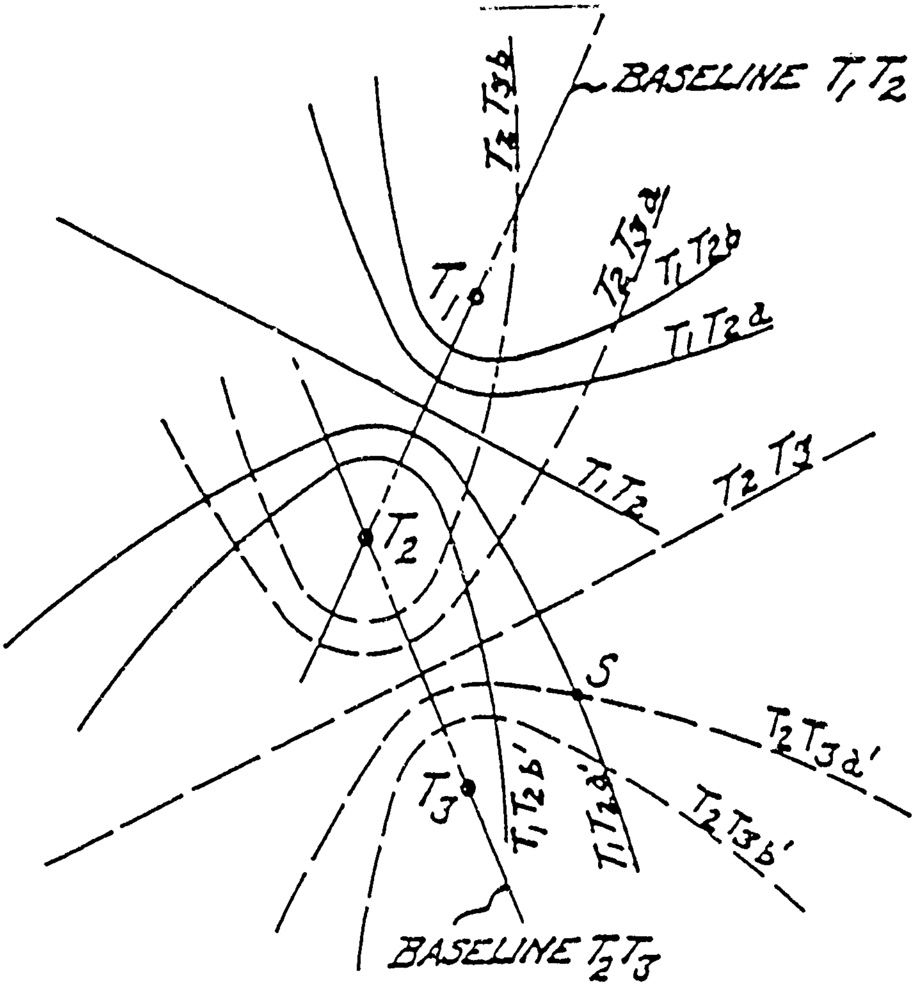
hyperbolic navigation system, and a ship S to be navigated. High powered pulses are sent out from a transmitter at station T_1 and also from a transmitter at station T_2. A constant known time difference is maintained between the instance of departure of these pulses, so that the time difference of arrival of the pulses as observed at a receiving point becomes a measure of the difference in distance of this receiving point from the two transmitters. It follows, then, that since a hyperbola is a curve that gives the locus of a point such that the difference in distances from any point on the curve to two fixed points is constant, a particular difference in distance corresponds to a receiving point located somewhere on that hyperbola. In the present instance this is hyperbola T_1T_2a' of the family of hyperbolas appearing between stations T_1 and T_2 as indicated in said FIG. 1. A second pair of transmitters, one located at station T_2 and the other located at stations T_3, can now be used to determine a second hyperbola, T_2T_3a' in the present instance, the intersection of which with hyperbola T_1T_2a' gives the position of ship S.

The several disadvantages of the navigation system described above have been substantially obviated by my invention which comprehends, in its simplest form, the use of a satellite relay station in combination with a single fixed ground station. As said satellite orbits within the field of view of automatic tracking radar apparatus located at said fixed ground station, its position is determined by the radar and indexed with time by a ground station clock. This position and time information is then telemetered to the satellite whose receiver-transmitter equipment relays it omnidirectionally to all ships located within its area of coverage. The ship, upon receiving said information, indexes it with shipboard time. After a suitable period of time the ship receives a second position message from the same satellite and indexes it with a new shipboard time. The two position messages thus received establish two points in space (focal points) and a baseline therebetween from which a hyperbolic surface of revolution can be established which intersects the earth's surface. At this point the navigator on the ship can establish a hyperbola, and he knows that he is somewhere on this hyperbola, but not exactly where he is on it. The distance is based on the primary fact that the transmission time taken by a pulse to travel over a distance is a measure of the distance. The unit of length in navigation computations may be called a light-microsecond; for example, 983.24 feet is the unit of length equivalent to a light-microsecond which represents the distance that a pulse travels in that time. In order for the navigator to locate himself definitely the ship receives a third position message which it indexes with a third shipboard time, thus establishing the second hyperbola. This second hyperbola because of the predetermined time difference must intersect the first hyperbola. Every intersection of these two hyperbolas represent measured time differences which is equivalent to measured distances and defines the fix of the position of the ship.

With reference now to accompanying drawings, FIGS. 2 and 3, and in conjunction with the several equations to be hereinafter developed, the various symbols used are herein defined as:

r=radius of the earth
h=altitude of the satallite
h(min.)=minimum altitude of the satellite
t_r=radar slant range of the satellite
t_r (min.)=minimum slant range of the satellite
t_s=range of the ship from the satellite
t_{ds}=time delay of satellite receiver-transmitter
t_{dg}=time delay of the ground station radar



PRIOR ART *Fig. 1*

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BY Wade [signature]
Willard R. Matthews, jr.
ATTORNEYS

March 24, 1964 I. D. SMITH, JR 3,126,545

SATELLITE HYPERBOLIC NAVIGATION SYSTM

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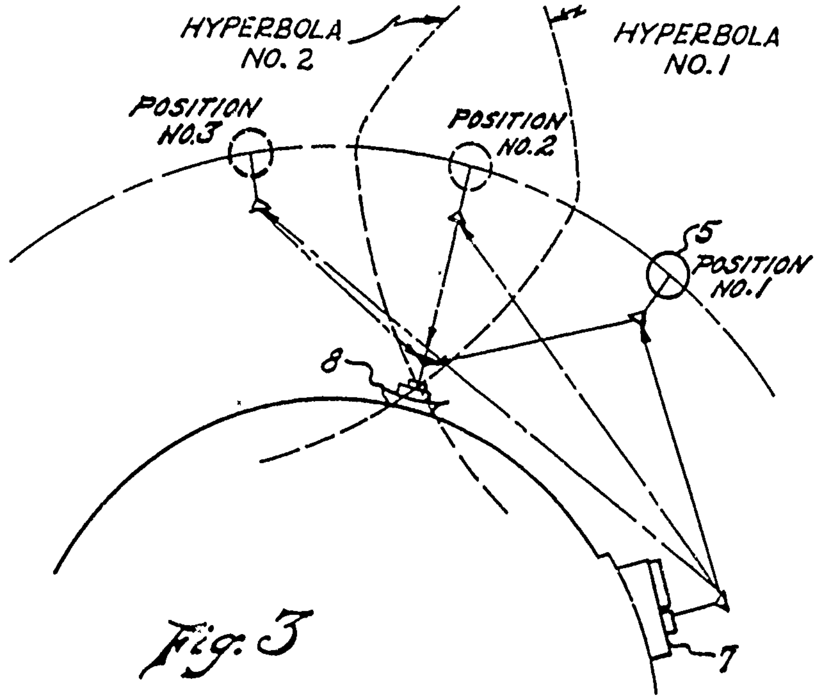
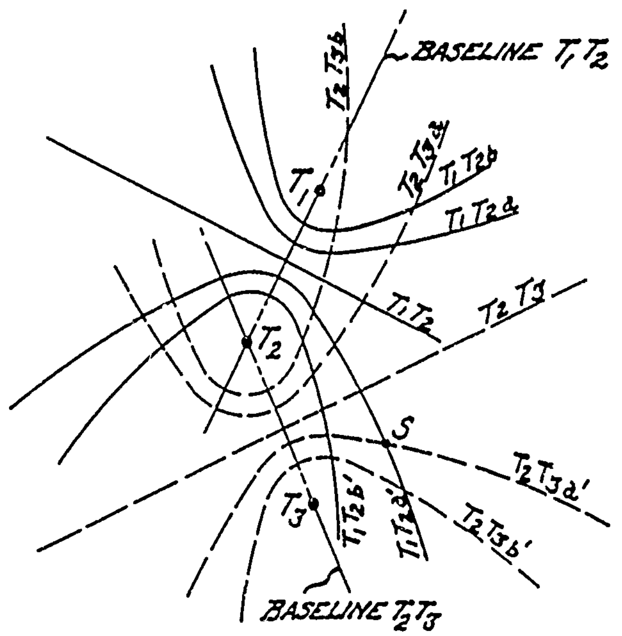


Fig. 3



PRIOR ART Fig. 1

INVENTOR.
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BY Willard R. Matthews, Jr.
ATTORNEYS

United States Patent [19]

Easton

[11] 3,789,409

[45] Jan. 29, 1974

[54] NAVIGATION SYSTEM USING SATELLITES AND PASSIVE RANGING TECHNIQUES

[76] Inventor: Roger L. Easton, 7704 Oxon Hill Rd., Oxon Hill, Md. 20021

[22] Filed: Oct. 8, 1970

[21] Appl. No.: 79,307

[52] U.S. Cl. ..... 343/112 R, 343/100 ST, 343/112 D

[51] Int. Cl. G01s 5/14, G01s 11/00

[58] Field of Search .... 343/112 D, 112 R, 100 ST

[56] References Cited

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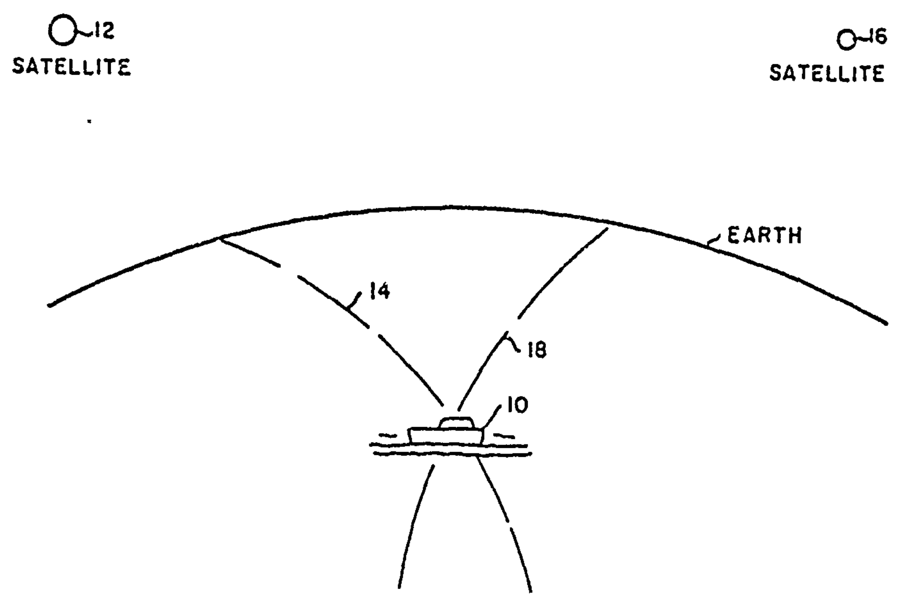
3,339,202	8/1967	Earp	343/112 D X

Primary Examiner—Richard A. Farley
Assistant Examiner—Richard E. Berger
Attorney, Agent, or Firm—R. S. Sciascia; Arthur L. Branning; J. G. Murray

[57] ABSTRACT

A navigation system wherein the navigator's location is obtained by determining the navigator's distance (or range) from one or more satellites of known location. Each satellite transmits multifrequency signals that are derived from a stable oscillator which is phase synchronized with the navigator's equipment that produces similar multifrequency signals. Phase comparison between the signals received from the satellites and the locally produced signals indicates both the distance between the navigator and the satellites and the navigator's location. In determining his location, the presence of the navigator is not revealed since no interrogatory transmission by him is required.

6 Claims, 3 Drawing Figures



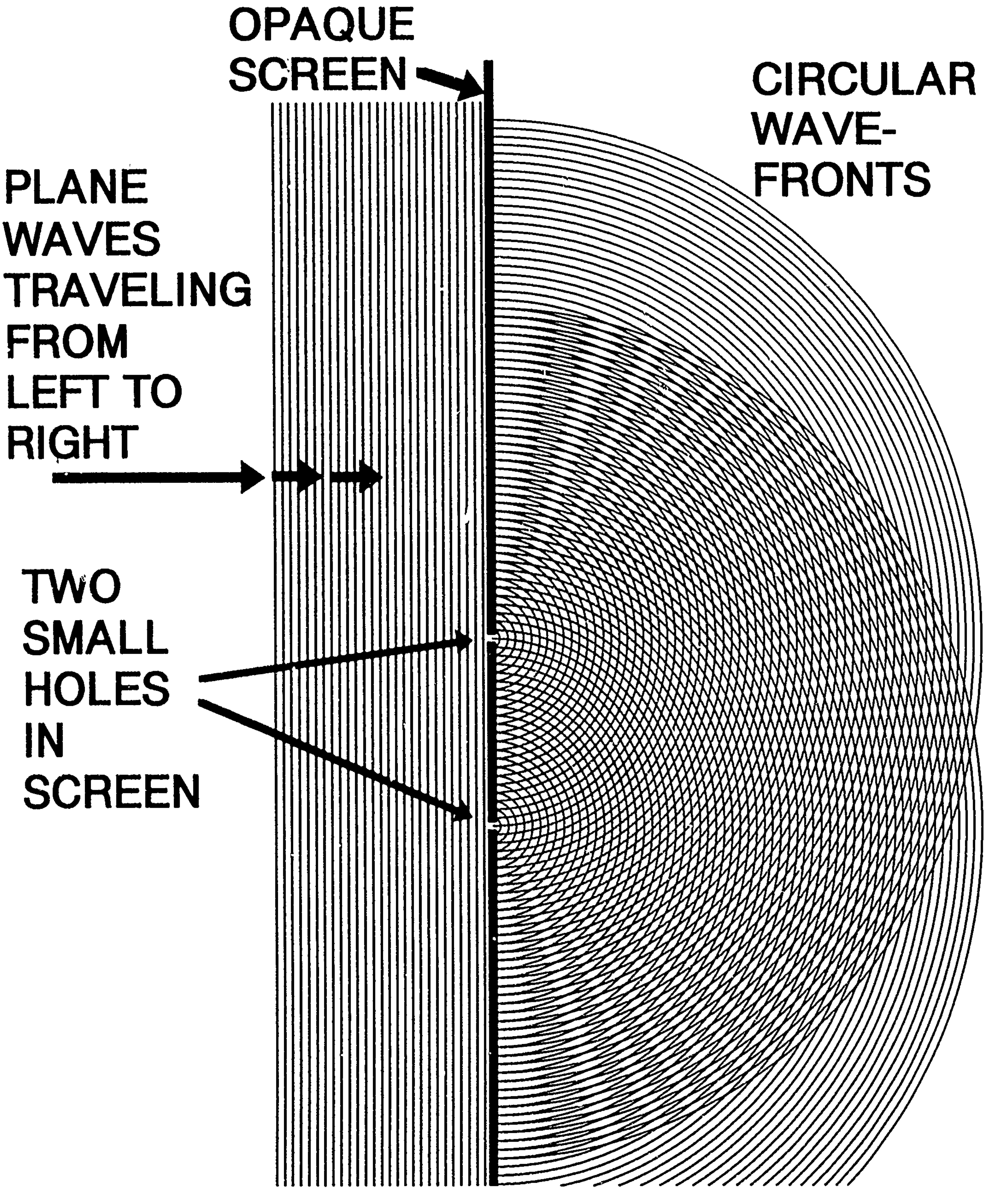
INTERFEROMETRY

- A wave has *phase.*

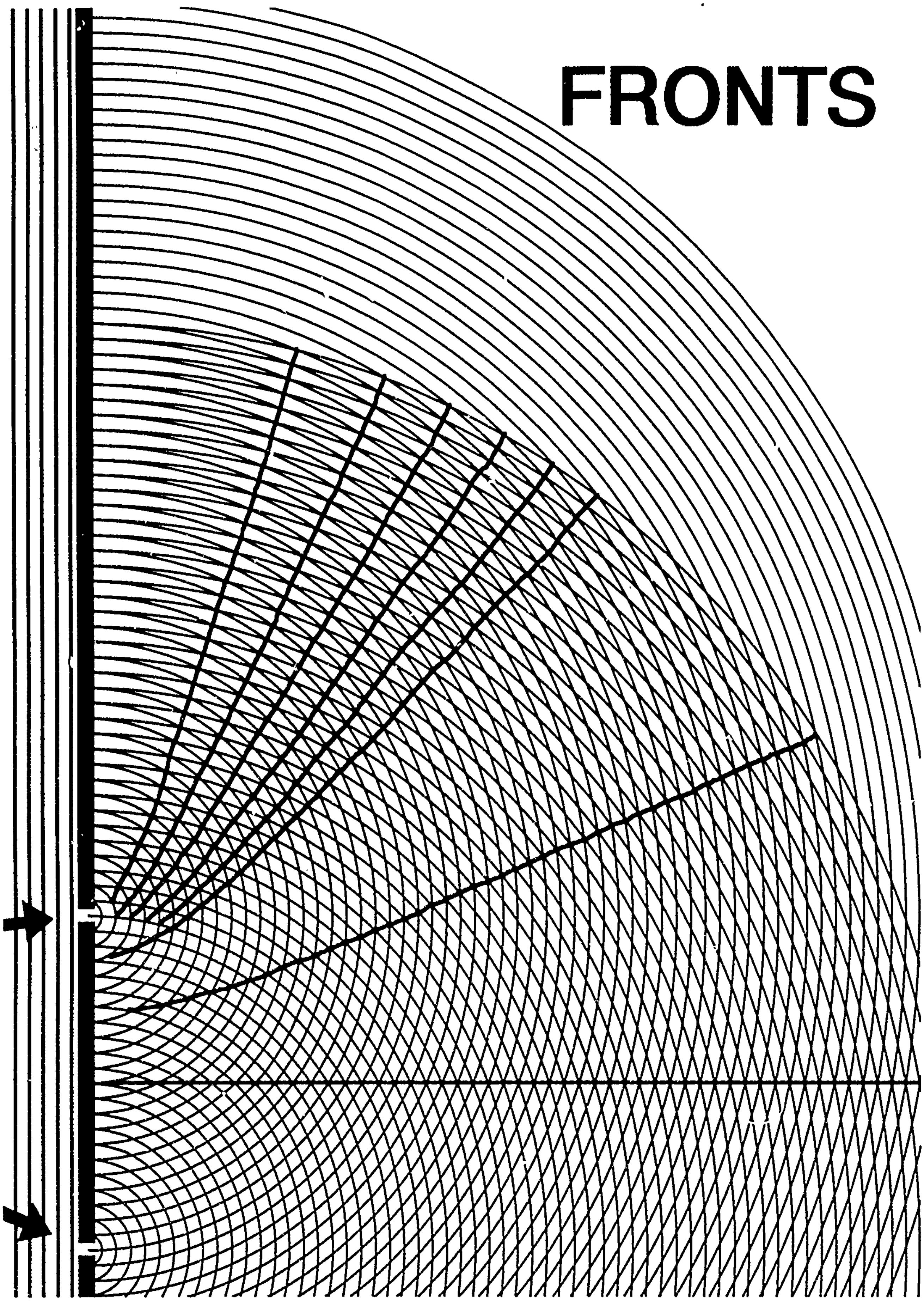
- Intensities of waves (unlike classical particles) don't add.

- Complex amplitudes (having magnitudes & phases) do.

- Interference of waves may be constructive or destructive or in-between, depending on their *phase difference.*


OPAQUE SCREEN
CIRCULAR WAVE-FRONTS
PLANE WAVES TRAVELING FROM LEFT TO RIGHT
TWO SMALL HOLES IN SCREEN

FRONTS



DIFFERENTIAL INTERFEROMETRY, or "DOUBLE DIFFERENCING"

- At each receiver, observe the phase difference between the signals being received from different satellites. (Result is insensitive to receiver phase.)

- Take the difference of these differences, between receivers. (Result is also insensitive to phase of either transmitter.)

Astronomical Applications of Differential Interferometry

Abstract. *Intercomparison of radio signals received simultaneously at several sites from several sources with small mutual angular separation provides a powerful astrometric tool. Applications include tracking the Lunar Rover relative to the Lunar Module, determining the moon's libration, measuring winds in Venus's lower atmosphere, mapping Mars radiometrically, and locating the planetary system in an inertial frame.*

In most applications of very-long-baseline interferometry (VLBI) the most serious limitations on the accuracy of the results are imposed by unknown, variable phase errors introduced by both the neutral atmosphere and the ionosphere above the receiving sites, and by fluctuations in the rate of the oscillators that provide phase references at the separate sites. These limitations may be largely removed in differential measurements, in which signals received simultaneously from different radio sources located close together in the sky are compared. If atmospheric and independent oscillator phase shifts affect observations of each source equally, their effects will cancel when differences between observations are examined. In this report we discuss several scientific applications of differential interferometry (*1*), as well as the actual tracking of the Lunar Rover performed during the Apollo 16 mission.

Because differential interferometry involves taking differences not only between receiving points but also between transmitting points, it follows that any potential source of error will cancel if it is common either to all receivers or to all transmitters. This simple principle will be shown to have important consequences for astronomical measurements. One such consequence relates to observations of artificial transmitters for which the carrier frequency may be uncertain and variable. Noninterferometric one-way Doppler tracking of such objects is ordinarily of little use because changes in the received frequency due to the Doppler shift cannot be distinguished from changes in the frequency of the transmitter itself. In interferometry, however, transmitter (and any other) frequency changes that appear equally at all receivers have no direct effect on the ability of the interferometer to determine relative angular positions. In fact, artificial radio sources make particularly convenient objects for interferometry because conventional Doppler counting techniques can be used to keep track of the phase of the carrier signal received at each site. Wide-bandwidth group-delay interferometry also may be done efficiently with artificial sources if the carrier wave is suitably modulated, for example, with a pseudorandom wave form of the kind often employed for two-way radar ranging (*2*). As in the case of one-way Doppler tracking, one-way radar ranging is ordinarily useless if either or both of the transmitter and receiver time bases are unstable. But for either phase delay or group-delay observables, the effects of transmitter instability cancel when the difference is taken between receiving sites (thus forming an interferometric observable), and the effects of receiver instability cancel when the difference is taken between a pair of transmitters (forming a differential interferometric observable).

We shall now discuss some of the potential scientific applications of differential interferometry. First, however, we describe one technical application already successfully carried out. Earth-based tracking of the Apollo 16 Lunar Rover relative to the Lunar Module. Three tracking stations (*3*) were employed so that two independent baselines were formed. Thus, two components of the motion of the Rover relative to the Module were determined from the changes in phase of the two differential interferometric observables. From the initial separation of the Rover and the Module and the constraint that the Rover remained on the lunar surface, it was possible to determine its entire path (Fig. 1). After a traverse of over 4 km, the final position computed from these data differed from the actual position by about 30 m, or about 0.015 arc second at the distance of the moon (*4*). The main source of error was relative phase drift between the two receivers (one each for the Rover and the Module) used at each site in this trial experiment. In an operational system this error would be eliminated by using a single receiver for both signals. The basic technique appears capable of reducing tracking errors to the meter level, a limit imposed by unmodeled lunar topography.

A related scientific application involves the accurate determination of the moon's libration by monitoring simultaneously from several tracking stations the ALSEP (*5*) telemetry transmitters located at three well-separated sites, such as those of Apollo 14, Apollo 15, and Apollo 16. Here, because the ALSEP's are fixed on the lunar surface,

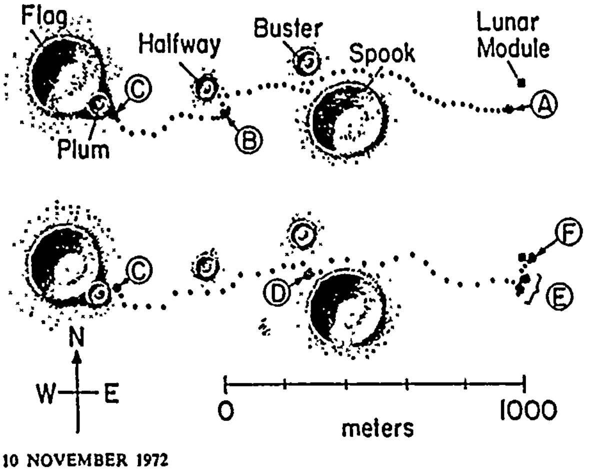


Fig. 1. The path of the Apollo 16 Lunar Rover is shown as determined by Earth-based differential interferometric tracking on 21 April 1972. Individual dots mark the positions obtained at 20-second intervals, beginning at 20:52:40 U.T. from point *A*. Craters given names by the astronauts are included for reference, although their locations are known only approximately. The Rover was stopped at point *B* for 6ᵐ20ˢ, at *C* for 1ʰ9ᵐ40ˢ, and at *D* for 27ᵐ0ˢ; several brief stops were made at *E*. At 23:03:40 our tracking indicated that the Rover had stopped finally at *F*, 30 m east of the Lunar Module; the Rover had actually parked at the Module. Some of this error may reflect a corresponding error in the assumed starting position, *A*. However, tracking data obtained while the Rover was known to be stopped occasionally showed systematic drifts as large as 2 or 3 cm/sec (see text). Random noise was less than 1 m. At all times during the traverse, position readings from the navigation system on board the Rover agreed within 100 m (approximately the limit of precision of the onboard system) with these differential interferometric tracking results.

DIFFERENTIAL VLBI: APOLLO 12-14 ALSEPS
GREENBELT, MD. - MERRITT ISLAND, FLA.

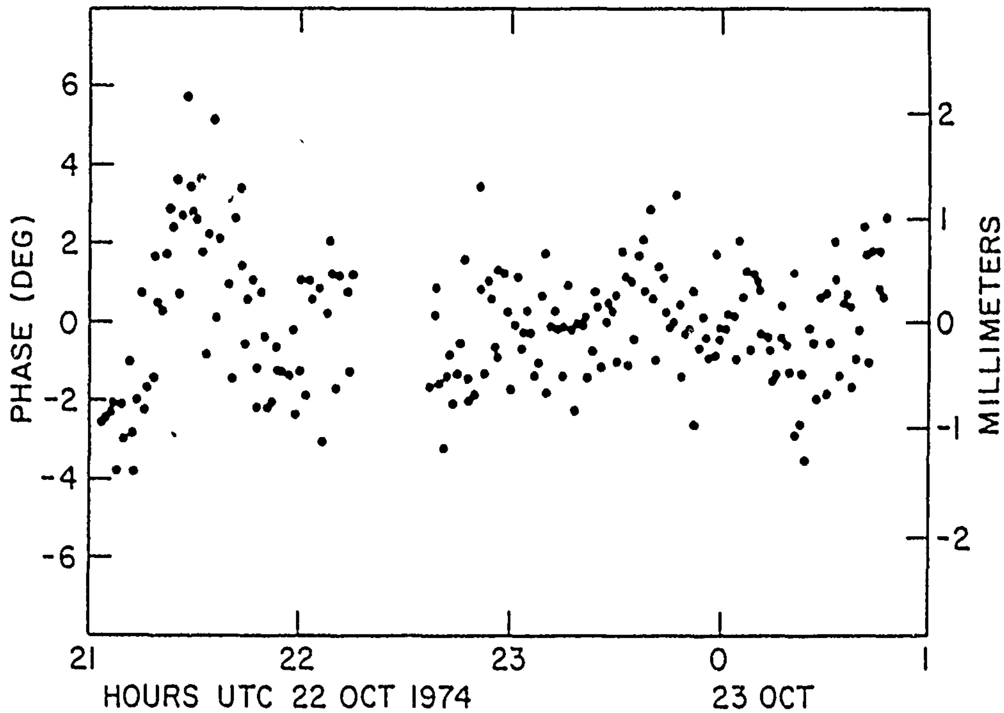


Figure 3 The precision with which instrumental and propagation-medium phase errors cancel in differential VLBI is demonstrated by these results from 13.2-cm–wavelength observations of a pair of Apollo Lunar Surface Experiments Package (ALSEP) transmitters performed with a 1200-km–long baseline by the author with H. F. Hinteregger, R. W. King, and I. I. Shapiro (unpublished). Three unknown parameters in a theoretical model of the differenced interferometric phase observable were adjusted to fit this approximately four-hour series of observations; the "post-fit residuals," or the differences between the observed and the corresponding theoretical values, are plotted here. The rms residual is 1.7° of phase, the equivalent of 0.6 mm of path length, or 5×10^{-10} of the baseline length. An equal phase change would result from a source-position change of the order of 5×10^{-10} radians, or 0.″0001.

Geodesy by Radio Interferometry: Determination of a 1.24-km Base Line Vector With ~5-mm Repeatability

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The 1.24-km base line vector between the two antennas of the Haystack Observatory was determined from X band radio interferometric observations of extragalactic sources via a new method that utilizes the precision inherent in fringe phase measurements. This method was employed in 11 separate experiments distributed between October 1974 and January 1976, each being between about 5 and 20 hours in duration. The rms scatters about the means for the vertical and the two horizontal components of the base line obtained from the 11 independent determinations were 7, 5, and 3 mm, respectively. The corresponding scatter for the base line length was 3 mm; the mean differed from the result obtained in a conventional survey by 8 mm, well within the 20-mm uncertainty of the survey. (The determination of the direction from the survey was too crude to be useful.) Another external check on our data was possible, since the azimuth and elevation axes of one of the antennas do not intersect but are separated by 318 mm. We estimated this horizontal offset from the radio interferometry data and found a difference of 10 ± 9 mm from the directly measured value, the relatively large rms scatter being due to the ~0.96 correlation between the estimate of this offset and that of the vertical component of the base line. Use of a newly completed calibration system in future experiments should allow the scatter to be reduced to the millimeter level in all coordinates for short base lines. For long base lines, such repeatability should be degraded only to about the centimeter level if calibrated observations with sufficient sensitivity are made simultaneously at two frequency bands. An assessment of the accuracy of either our present or future base line results awaits the availability of an accepted, more accurate, standard for comparison. Nonetheless, base line changes can be determined reliably at any established level of repeatability.

1. INTRODUCTION

The technique of very long base line interferometry (VLBI) has been under development for several years to enable vector base lines to be determined between arbitrary points on the earth's crust from observations of extragalactic radio sources [*Shapiro and Knight*, 1970; *Hinteregger et al.*, 1971, 1972; *Shapiro et al.*, 1974; *Thomas et al.*, 1976; *Ong et al.*, 1976]. A major goal of this continuing effort is to reduce the uncertainty in such determinations to the millimeter level for short base lines and to the centimeter level for intercontinental base lines, the observations extending over about 8 hours or somewhat less in each case. We have recently used radio interferometry to determine, in 11 separate experiments, the rather short 1.24-km base line between the Haystack and Westford antennas of the Haystack Observatory in Westford, Massachusetts. Our purpose was twofold: (1) to demonstrate the effectiveness of a new method that we developed to use measurements of group delays (see, for example, *Shapiro* [1976]) to eliminate the '2π' ambiguities in the far more precise measurements of phase delays, so that the latter could be employed for the determination of the base line and (2) to separate, to a high degree, the purely instrumental contributions to the errors in the base line estimates from all other contributions, such as those caused by inadequacies in our model of the propagation medium.

2. DESCRIPTION OF EXPERIMENTS

In Table 1 we show the relevant parameters of the antennas and receivers used. The remainder of the interferometer system was the same as is described by *Whitney et al.* [1976]. At Haystack the X band ($f \approx 7850$ MHz) signals received from the extragalactic radio sources were converted to base band (0–360 kHz), clipped, sampled, and recorded digitally on magnetic tape. The same procedure was followed at Westford except that the intermediate frequency signals were carried by a sufficiently stable cable to Haystack, where, solely for convenience, the final operations on the signals were performed. The local oscillators used in the frequency conversions were switched over about a 100-MHz range in order to obtain adequate group delay resolution. The group and the phase delays through each receiving system were monitored continuously by injecting a low-level calibration signal, derived directly from the local frequency standard, into the receiver 'front end.' Unfortunately, cable measurement systems to monitor the variations in the delays of the calibration signals incurred between the frequency standards on the ground and the receiver front ends on the antennas were not available for these experiments. These variations were due to a combination of flexure and temperature effects. Although each type of effect can introduce variations of about 1 cm in electrical path length, the cables on the antennas often suffer rapid flexure

[1] Also at the Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

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0148-0227/78/017B-0850$03.00

Miniature Interferometer Terminals for Earth Surveying

Charles C. Counselman III and Irwin I. Shapiro
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Abstract. A system of miniature radio interferometer terminals is proposed for the measurement of vector baselines with uncertainties ranging from the millimeter to the centimeter level for baseline lengths ranging, respectively, from a few to a few hundred kilometers. Each terminal would have no moving parts, could be packaged in a volume of less than 0.1 m^3, and would operate unattended. These units would receive radio signals from low-power (<10 w) transmitters on Earth-orbiting satellites. The baselines between units could be determined virtually instantaneously and monitored continuously as long as at least four satellites were visible simultaneously. Acquisition of the satellite signals by each terminal would require about one minute, but about one second of signal integration, and the collection of only a few kilobits of data from two receiving units would suffice to determine a baseline. Different baseline lengths, weather conditions, and desired accuracies would, in general, dictate different integration times.

The system proposed here could be used to monitor the regional accumulation and release of strain preceding, following, and even during earthquakes. The terminals could be deployed in arrays of various dimensions and densities. Their use could also include monitoring variations in transcontinental and intercontinental baselines, but with reduced accuracy. Comparisons with other systems proposed for extensive measurements of regional baseline vectors appear to favor this interferometric approach.

I. Introduction

The technique of very-long-baseline interferometry (VLBI) is only a decade old and barely approaching adolescence. Nonetheless this radio interferometric method has seen broad application, especially in astronomy. In geodetic applications, the demonstrated level of repeatability of baseline-length determinations ranges from ~3 mm for ~1 km distances (Rogers et al., 1978) to ~3 cm for transcontinental distances (Robertson et al., 1979). This combination of precision and range should make VLBI a very powerful technique for monitoring the time dependence of regional and continental baselines. Yet it is still not widely used for this purpose. Why? A principal reason has been cost. Applications of VLBI to geodesy have hitherto involved observations of the random, weak, radio signals received from distant, extragalactic, sources. The achievement of useful signal-to-noise ratios with these sources has dictated the use of large diameter antennas, expensive atomic frequency standards, and wideband tape-recording and correlating systems.

In contrast, only very small, simple, and inexpensive ground equipment is required to utilize the relatively strong, precisely controlled, radio signals that can be transmitted from Earth satellites. Nonetheless, although several methods have employed satellite signals to determine baselines, none of these methods has yet achieved the measurement precision demonstrated with VLBI. Why not? What is the "secret ingredient" of the interferometric technique? Basically it is the use of differencing. Interferometry, *per se*, involves the differencing of the phases of signals received at the two ends of a baseline. With properly designed equipment, the inherent "2π" ambiguity in these phases of radio signals from a given source can be eliminated, and advantage taken of precise phase measurements of the signals from several sources, to determine a baseline with an uncertainty equal to a small fraction of the wavelength of the radio signals. Further, this baseline determination does not depend on the signals from any source having any particular temporal regularity.

The baseline vectors determined by radio interferometric techniques can be related to the best known approximation to an inertial frame: the positions in the sky of compact, extragalactic, radio sources. Of course, when the baseline vector is determined from interferometric observations of radio signals from satellites, an extra step is required to relate the positions of the satellites to those distant radio sources. Again, the technique used is interferometric but, here, use of the full panoply of the conventional VLBI armamentarium is required.

A system that combines the advantages of VLBI with the benefits of strong satellite signals could open a new era in geodesy. We describe a relatively simple system here. It would employ compact ground equipment with no moving parts and low-power radio transmitters on a set of satellites. We dub this combination the Mighty MITES system, MITES being an acronym for Miniature Interferometer Terminals for Earth Surveying (or, to be presumptuous and facetious simultaneously, the Massachusetts Institute of Technology Engineering Success). Our system appears

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NASA Conference Publication 2115

Radio Interferometry Techniques for Geodesy

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held at the Massachusetts Institute
of Technology, Cambridge, Massachusetts
and the Northeast Radio Observatory
Corporation Haystack Observatory,
Westford, Massachusetts
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NASA

BACKPACK VLBI TERMINAL WITH SUBCENTIMETER CAPABILITY

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The measurement of short vector baselines with subcentimeter repeatability and accuracy using radio interferometric observations of quasars has already been demonstrated (reference 1). This paper describes our plans to achieve comparable performance using inexpensive, backpack portable equipment that processes less than one second of data per baseline redetermination. Figure 1 summarizes some of these objectives.

Our approach exploits the full measurement accuracy inherent in the precise radio signals that will be broadcast by each satellite in the NAVSTAR Global Positioning System (GPS) (reference 2). Figure 2 illustrates the measurement concept. The user equipment at each end of the unknown baseline receives signals from the same set of four or more GPS satellites. The equipment consists of a simple antenna, a GPS receiver, a microprocessor unit and a recording unit (reference 3). "Real-time" baseline determination can be accomplished by linking the microprocessor units with a communication channel that can transmit at the rate of about 1 kilobit per baseline redetermination.

Each GPS receiver measures its range to each satellite by means of the wide-band pseudo-noise P-Code modulation that is impressed on the GPS radio frequency carriers which are at 1.226 GHz and 1.57542 GHz (reference 4). These measurements will typically have a precision of about 0.5 meters, which is approximately 2.5 wavelengths at a frequency of 1.57542 GHz. The primary use of these relatively coarse measurements in the proposed program is to assist in resolving ambiguities of the more precise carrier-phase measurements that will also be made (see below).

- TO DEVELOP BACKPACK PORTABLE EQUIPMENT TO MEASURE VECTOR BASELINES FROM ~ 1 KM TO ~ 100 KM IN LENGTH WITH SUBCENTIMETER TO FEW CENTIMETER ACCURACY.

- TO DEVELOP EQUIPMENT THAT IS
  - SIMPLE IN CONCEPT AND IMPLEMENTATION
  - RELIABLE IN UNATTENDED OPERATION
  - INEXPENSIVE - LESS THAN $15,000 PER UNIT

Figure 1. Objectives.

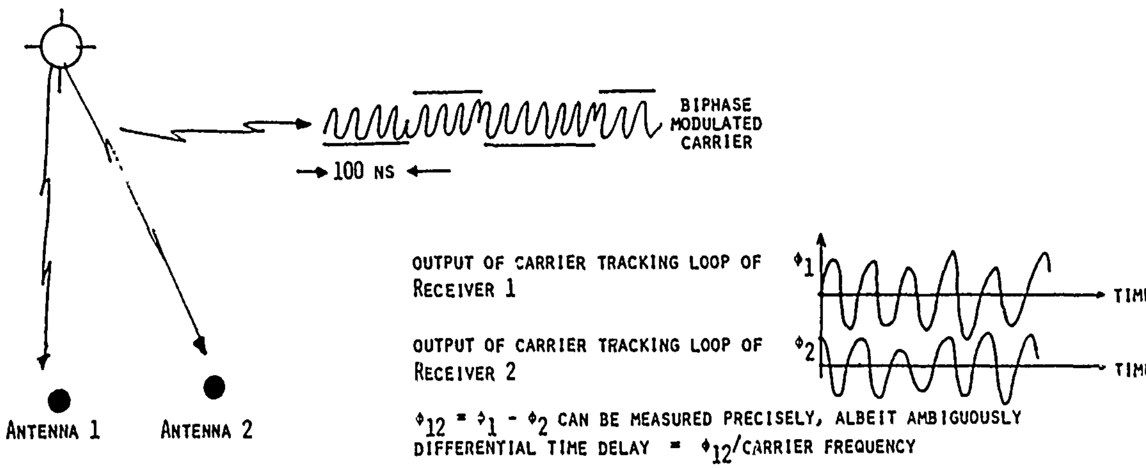

Figure 3. GPS signal processing concept ("reconstructed carrier").

This technique is described in reference 1. We note that all data used to resolve ambiguities are usable also for accurate determination of the baseline vector, after the ambiguities are resolved.

2. Measure the phase difference between the two GPS carriers received at each end of the baseline from each satellite to within a few degrees (note that both GPS carriers are synthesized coherently from the same oscillator). The corresponding phase-delay ambiguities will be light-time equivalents of integral multiples of the 0.43 m half-wavelength for the difference frequency (349 MHz). This approach is similar to the use of multiple tones in OMEGA to resolve "lane" ambiguities (reference 7). Used in conjunction with the coarse range measurement, the phase from both GPS carriers will allow a reduction in the initial ambiguities of the phase delay estimates. As the baseline length increases, the effectiveness of this technique will decrease because of ionospheric effects.

As the first phase in the development of the intended system, we plan to conduct an experimental program using commercially supplied GPS receivers. One or more standard baselines defined by receiving antennas will be established and surveyed. Each leg will be less than 100 meters in length. GPS signals received by the antennas will be processed to make a series of baseline determinations under a wide range of environmental conditions. The objectives of this experiment are:

1. to ascertain whether the accuracy of the baseline determination meets our goal (see figure 4);

2. to assess different techniques for ambiguity resolution; and

3. to determine whether the present GPS signal structure will allow the development of inexpensive and effective ground equipment.

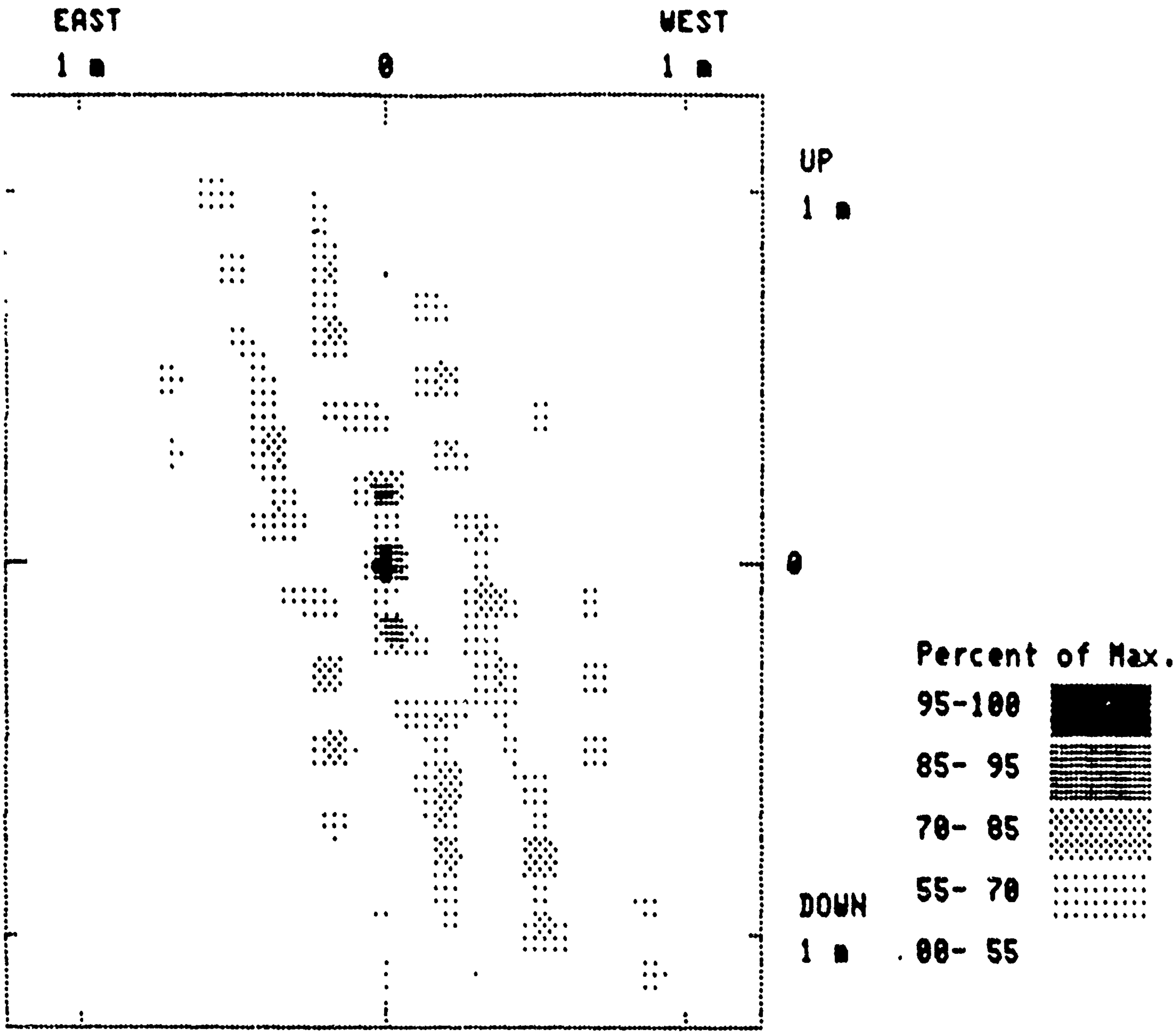

Fig. 1. Map of the baseline-vector ambiguity function $R(\hat{b})$ defined by (3), for simulated, error-free, observations spanning 15 min. This map is of a particular, but typical, vertical plane that contains the true value of the baseline vector at the origin. Certain fine details of the map are computational artifacts and should be ignored. In particular, there are just 25 horizontal and 25 vertical resolution elements, whose centers do not generally coincide with peaks of the function mapped. The function is actually symmetric, with $R(\vec{b} + \Delta\vec{b}) = R(\vec{b} - \Delta\vec{b})$.

Sub-Centimeter-Accuracy Surveying Could Have Been Done With TRANSIT* But Wasn't Because...

- *Phase* was not observed.

- A plurality of satellites was not simultaneously observed.

  Having more than one satellite in view was believed to be a *bad thing.*

  The satellite orbits were deliberately arranged to keep this from happening.

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*and still could be, *e.g.* by modifying a MACROMETER® antenna and front-end to receive the TRANSIT frequency of 400 MHz. Observing two satellites simultaneously for two successive passes can give GDOP as good as GPS!

TRANSIT Satellite Doppler Positioning People Believed That GPS Would Be Inferior For Geodetic Surveying.

- GPS signals have less Doppler shift.

- GPS "geodetic" receivers available — and planned — in 1980 observed (pseudo)range and Doppler but *not phase.*

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IN REPLY REFER TO:
K13:BRH:ccs
5236

MAR 3 1 1980

From: Commander, Naval Surface Weapons Center
To: Johns Hopkins University/Applied Physics Laboratory
Attn: Reggie Rhue
Johns Hopkins Road
Laurel, Maryland 20810

Subj: Procurement of a Field Portable Geodetic Receiver; request for

Encl: (1) Specifications for a Field Portable Geodetic Receiver

1. The Naval Surface Weapons Center (NSWC) has been tasked with the responsibility of procuring a Field Portable Geodetic Receiver in accordance with the specifications as outlined in enclosure (1).

A. System Concept

This unit will provide the geodetic community with a flexible GPS receiver-computer combination with the capability to calculate a static geodetic position in the field. Size, weight, power, and environmental specifications will be such that a small team of surveyors would be able to carry the unit and its supporting equipment to the various sites of interest, set up, operate, and obtain 2-3 meter absolute position accuracy in near real time. Alternately rapid satellite switching can be used in coordination with similar systems at other sites to obtain phase data for a precise relative positioning capability.

In addition to the calculation of absolute position on site, the system will have a recording device which can be used to record data and load software programs, and a keyboard for operator interface with the system. Transmission of data from the recorded tape via modem to a computer center will also be an option.

The system will consist of two main sections: the receiver module and the real time processor module. The remainder of this memorandum will address the receiver module only.

B. Receiver Capabilities

(1) The receiver will consist of a single satellite channel which will provide simultaneous L_1 and L_2 measurements of pseudo range and Doppler.

Eos, Trans. AGU, vol. 62, No. 17, p. 260, April 28, 1981

ACCURACIES OF BASELINE DETERMINATIONS BY MITES ASSESSED BY COMPARISONS WITH TAPE, THEODOLITE, AND GEODIMETER MEASUREMENTS

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On Dec. 17, 1980, portable MITES antennas [ref. Bull. Geod. 53, 139-163 (1979)] were set atop three survey marks near the Haystack Observatory building. These antennas yielded radio interferometric observations of the NAVSTAR/GPS satellites which were analyzed to determine the vector baselines between the survey marks. Observations were repeated 12 days later with different antennas on the marks. For the determination of each baseline on each day all of the observations from the entire time that five satellites were above 20° elevation--1.3 hours--were used. No data were deleted or downweighted and the same parameters were estimated using the same algorithm in every case. On each day, the triangle of separately estimated baselines closed within 1 cm in each vector component; and for each baseline, the two determinations agreed within 1 cm. In January, 1981, the firm of H. Feldman, Inc., surveyed the triangle conventionally by means of steel tape, 1" theodolite, laser Geodimeter, and precise level. The MITES experimenters and the conventional surveyors did not communicate, but both delivered their results in writing to a referee (R.L.G.) for comparison. The results for the lengths of the sides of the triangle were, in millimeters:

	Side 1	2	3
Tape	64,944 ±5	92,063 ±5	123,805 ±5
MITES	64,944 ±7	92,067 ±5	123,816 ±7
Geodimeter	n.a.	92,074±10	n.a.

We conclude that, at least for short baselines, the resolution of interferometer fringe ambiguities is not difficult; also, at the centimeter level of accuracy, multipath interference is not a significant problem with MITES.